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MEMOIR

ON

Foundations in Compressible Soils,

WITH

EXPERIMENTAL TESTS OF PILE-DRIVING,

AND

FORMULA FOR RESISTANCE DEDUCED THEREFROM.

COMPILED BY

RICH'D DELAFIELD, Bv't Maj. Gen'l,
Corps of Engineers, U. S. Army, Member of the L. H. Board.

WASHINGTON, D. C., *Dec. 1, 1868.*
PUBLISHED BY ORDER OF THE LIGHT-HOUSE BOARD.

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WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1878.

N. M.

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Memoir on Foundations in Compressible Soils in connection with the adoption of a suitable artificial foundation for a light-house at the Southwest Pass of the Mississippi river.

The following notes on the *practice* and *experience* of American and European engineers on foundations in very compressible soils are collected for the consideration of the committee of the Light-house Board, to which was referred the different projects heretofore submitted for a foundation for a light-house to be constructed at the Southwest Pass of the Mississippi river:

The soundings off the mouth of the river to the westward along the Louisiana and Texas coasts, and to the northward along the Chandeleur Islands, and thence eastward along the coasts of Mississippi and Alabama, all indicate sandy bottom beyond the immediate influence of the rivers. The advance of the delta of the Mississippi into the Gulf of Mexico is composed of alumina and vegetable matter overlaying this sandy bed. The depth of the sand below the waters of the river and gulf appear to be beyond our reach as a base on which to rest any artificial structure, and the surface of the soil created by the deposits of the freshets is so deficient in solidity as to be designated very appropriately "*prairie tremblante.*" We have to combat the difficulties presented by this overlaying compressible mass. It is formed during the annual freshets of the rivers by deposits, in eddies and slack water, of the matter abraded by the current from the shores and banks of the different rivers as their freshets are thrown into the Mississippi, and not thrown up or translated along the coast by the ocean wave. These deposits from the tributaries of the Mississippi valley vary in specific gravity, are deposited during the annual freshets in proportion to their gravity, and combined with more or less water in the porous mass form strata of varying density overlaying each other, and constitute the accumulation from year to year.

A remarkable feature in this alluvial formation is the upheaval by some unaccountable power of islands that consist of the deep seated strata, raised and forced up many feet above the level of the gulf and annual freshets, leaving cavities beneath them, and an element of destruction in the continued discharge of matter mixed with water thrown up for an indefinite period after their first and sudden eruption and formation. They have been sufficiently described in previous reports to the Board, on its files, and now only referred to for indicating localities the engineer should studiously avoid as beyond his power of adaptation for foundations of heavy structures, and, with the previous introductory remarks, to be considered with the projects of engineers for other difficult localities now to be noticed. (See House Document No. 7, 1st session of the 21st Congress.)

HOLLOW IRON CYLINDERS SUNK BY ATMOSPHERIC PRESSURE.

This system has been applied successfully in Europe and America. Having been proposed for the Southwest Pass light-house, the following notes are submitted explanatory of its advantages and applicability in certain localities:

The first application of this principle is mentioned in Ure's Dictionary of Arts and Manufactures as having been tried on the Loire, in France, by Triger, in sinking a *shaft* 65 *feet*. A detailed account of Mr. Triger's system is to be found in the Comptes rendus de l'Academie des Sciences. The principle was applied by Mr. Hughes in sinking the piles at Rochester bridge, England. With his modifications it has entirely superseded the ordinary diving-bell for foundations in deep water. Compressed air is made to free a hollow pile from the water within it after it has been placed in its situation, (the bed of the river or other place,) there used as a diving-bell, without again being drawn up, and remains as a part of the permanent structure.

Mr. Hughes sunk, on the Rochester side of this bridge, 12 cylinders or piles, and 30 on the Strood abutment; each pile consisting of 2 or 3 or more sections of cylinders, 9 feet in length, 7 feet in diameter, bolted together through stout flanges, the bottom having a *beveled* edge. For a description of sinking these piles, see Crecy's Supplement to his Encyclopædia of Civil Engineering, London, 1856. Mr. Hughes' system is admirably shown on a large scale, with all its important details, in a work published by him in England.

The agents of Dr. Potts, as a patentee, introduced it in this country, and it was successfully used by Mr. Gwynn for a railroad bridge in South Carolina, in a *sandy bed* of the Pee Dee river. Mr. McAlpine has used it with success for a bridge over the Harlem river, N. Y., in a *muddy* and sandy soil, and at this time it is being applied on a more enlarged scale under the Light-house Board, by General W. Sooy Smith, in the construction of a wall around the light-house at Waugoshance, in Lake Michigan, in a *gravelly and rocky bed.*

The Clyde or Nethan viaduct is carried on cast-iron cylinders, sunk in the *sandy bed* of the river, filled up to the level of flood-tide with concrete, leaving upwards of 40 *feet of the upper portion of the cylinders without any filling.* (Engineer and Architectural Journal, November, 1864.)

In the construction of the centre pier of the Albert bridge, at Saltash, on the Cornwall Railway, a *wrought-iron* cylinder, 37 *feet* in diameter, and 90 *feet high,* open at *top and bottom,* was sunk *through the mud to the rock.* It was expected that, forming a bank around the cylinder after being sunk to the rock, would exclude the water.

The cylinder was constructed to admit also of *air pressure;* the surface of the rock was inclined 6 feet lower on one side than the other; the iron cylinder was shaped to conform with the rock; a dome or lower deck was constructed inside at the level of the mud, 13 feet below the surface of the water; and an internal cylinder, open at top and bottom, connected the lower with the upper deck of the cylinder; a 6-foot cylinder was fixed eccentrically inside the other, and an air-jacket or gallery, making an inner skin around the bottom edge below the dome, was formed about 4 feet wide, divided in 11 compartments, and connected with the bottom of the 6-foot cylinder by an air passage below the dome.

When the 37-*foot cylinder* was thus constructed, it was towed to and accurately adjusted over the intended site; water was then let in, until the cylinder penetrated through 13 feet of mud, and rested on some irregularity, causing it to keel over about 7′ 6″. By letting water in upon the dome or lower deck, and loading the higher side with iron ballast, the cylinder forced its way through the obstruction at the bottom edge, and took a nearly vertical position.

The *air and water pumps* were then worked, and the greater part of the *mud and oyster shells* which filled the compartments of the air-jacket was cleared out, and the irregular surface of the rock excavated—the *bottom of the cylinder being now* 82 *feet* below high-water line. A ring of ashlar stone, 4 feet wide and 7 feet high, was then built in the air-jacket, and a bank of clay and sand was deposited around the outside of the cylinder to compress the mud.

When the water was pumped out the body of the cylinder below the dome, and the excavation of the mud was being proceeded with, a leak broke out and the water overpowered the pumps. Recourse to air pressure in the body of the cylinder below the dome was determined upon and arrangements made therefor.

The 37-foot cylinder was loaded with 750 tons of ballast when the pumps succeeded in keeping the water down; the mud was then excavated, the cylinder below the dome securely shored across, and the rock leveled, when the masonry was commenced in the body of the cylinder.

As soon as the masonry reached the level of the air-jacket ring the plates of the air-jacket were cut out, and the two masses of masonry were bonded and thus united, forming a single mass. Upon the top of the bonding course of masonry two courses of brick were laid in cement, making a water-tight floor over the whole diameter of the column.

The next operation was to draw off the water above the dome and remove the ballast, allowing the masonry within to proceed. After the masonry had been completed to the plinth course the upper part of the cylinder was unbolted at the separate joints and floated to the shore.

The roadway is 100 *feet above high-water* mark. This centre pier supports iron arches of 455′ *span each* from the centre of the river. (Engineer and Architectural Journal, 1862 and 1864.)

Bridge over the *Harlem river*, on cast-iron cylindrical piles, by Wm. J. McAlpine. The draw pier of this bridge was composed of *one central* and *ten circumscribing iron columns*, each 6 *feet in diameter* and 50 *feet in heighth*—the water being 20 feet in the deepest part. These piles were sunk by the pneumatic process, (both plenum and vacuum.) It was deemed advisable to increase even the large base, due to the size of the column formed by these cylinders.

It had been decided to fill the columns with concrete; and it was suggested to extend this masonry below the bottom of the iron cylinders, (as the men could work in water,) undermining the adjacent earth as far as practicable, and to extend the concrete into the space thus undermined. This was done in sections of about 2 feet in width; and, when the rim had been completed, it was found that the column was virtually extended, and that the water would readily sink, under the pneumatic pressure, to a level with the bottom of the concrete, so that the sand within it was easily removed, and the space filled with concrete to a depth, generally, of 4 feet or more. The cement set with *greater rapidity under pneumatic pressure* than in the *open air*.

The last column was driven from 16 to 20 feet, in from 3 to 6 days, in sand and porous material, free from obstruction; 12 men, all told, sufficed to do the work, including engine-drivers, stevedores, and foremen. The metal in the columns was $1\frac{1}{4}$ inch thick. No ill effects were experienced by the workmen from a pressure of $2\frac{1}{2}$ atmospheres.

In some cases the pile could be sunk by the vacuum process alone; in all other cases by the plenum, and sometimes both might be employed with advantage, and further aided by weight or pressure on the heads of the cylinders.

The support of these iron columns, derived from friction on the exterior surface, was found to be $\frac{1}{2}$ a ton per square foot, but in the finest earth it would amount to 3 tons.

The support from the area of the bottom in shallow depths was from 5 to 10 tons per square foot. (See Engineer and Architectural Journal for January, 1868.)

This system is perfectly reliable in all cases where the compressible soil can be removed and a hard bottom reached on which to found the contemplated structure. It was practiced with great success in the construction of the Theiss bridge, and minutely described in the Annales des Ponts et Chaussées, 1859, and Annales du Chimie, (1841.) Mr. McAlpine gives much useful and practical information on this subject in the February and March numbers of the Journal of the Franklin Institute. For a founda-

tion at Waugoshance, Lake Michigan, on this system for a wall of 8 feet thick, and laid 12′ 3″ below the surface of the water, 7 feet of which was through gravel and large boulders, enclosing an elliptical area of 67′ by 49′, under one wrought-iron cylinder, with air-pumps and valves, see the Report of the Light-house Board, accompanying the Report of the Secretary of the Treasury for December, 1868, pp. 71 and 72.

PILE FOUNDATIONS.

The next system for consideration is that of piles driven into the ground, on which the superstructure rests directly, or through the intervention of a floor of wood or masonry. It is deserving of particular attention from its probable fitness for the locality under consideration at the Southwest Pass of the Mississippi river.

FOUNDATIONS ON WOODEN PILES.—AMSTERDAM.

The most extensive and oldest application of pile-driving for foundations to which instructive reference is at command is in the city of Amsterdam. The original site of this city was a salt marsh. All the buildings, (28,000,) for a population of 224,000 souls, (in 1850,) covering a surface of 900 acres, are supported on piles of from 50 *to* 60 *feet in length.* After passing through a mixture of peat and sand of little consistence, at a depth of about 40 feet, they enter a bed of firm clay. The ends of the piles are sawed level, and covered with *thick plank,* on *which the masonry is constructed.* Though the houses have declined from the perpendicular, they are considered to be quite secure against falling; yet such a contingency occurred in 1822, by the sinking and total ruin of a large stack of warehouses heavily filled with corn—(wheat in bulk that shifted the weight.)

The palace built in 1648 is supported on 13,659 piles. It is 282 feet long, 235 feet wide, and 116 feet in height, exclusive of a cupola of 41 feet.

The steeple of the Oude Kirk is 240 feet high. The surface or level of the natural ground is below the level of the ocean.

FOUNDATIONS ON WOODEN PILES AND CAISSONS IN THE BED OF THE THAMES, LONDON.

The labors of engineers in the valley of the Thames river, at and about London, give much useful information in the construction of ancient as well as modern pile foundations.

Old London bridge was commenced in 1176, and finished about 83 years thereafter. The piers rested on piles driven *only* around the outside of the pier, so placed as to carry the *whole weight.* They were of elm, and at the expiration of six hundred years, on being drawn up, remained without material decay. A part of this bridge fell about 100 years after it was finished; and the whole structure was removed to give place to the new bridge in 1825.

Old Westminster bridge was built between 1733 and 1747. Piles were used under one pier only. Its piers (with the one exception) were constructed in caissons or flat-bottomed boats. Each caisson contained as much timber as a forty-gun frigate. They were 80 feet long by 30 feet wide. These foundations failed; the caisson bottoms or floors sunk in the middle; the sides and ends projecting beyond the stone work broke off and bent upwards. The sinking of the bearing area of the substratum, under the partial and unequal pressures of the floors of the caissons, has had more to do with the failure than any other defect.

Black Friar's bridge was built between 1760 and 1771. The foundations were laid in caissons, the floors of which rested on piles about 9 feet apart—*only* 45 *piles to each caisson*—and intended to obtain a level surface on which to rest the floor, to settle down to a uniform bearing. Its stability, says Rennie, for many years is to be attributed to these piles. It has since failed, and requires large expenditures on repairs.

It was believed in this case, as at Westminster, that if the scour of the river bed could be prevented, and nothing carried away from under the foundations and about the piles by external agency, the clay base would support the gravel stratum above it, and the gravel the stone; but the pressure per foot in the Westminster was nearly 5½ tons, and in Black Friar's 5 tons per square foot; and clay, when the pressure is at great depths within it, will not bear 5 tons per foot.

Waterloo bridge, built between 1809 and 1817. The foundations of the piers of this bridge are built in coffer-dams or caissons, the floors of which rest on *piles,* about 3 *feet* apart, under the entire base of the pier, penetrating the clay about 18 *feet.* The foundation is arranged with plank, concrete, and stone, as in the New London bridge. The estimated *pressure per foot* on the head of each pile is, in this case, about 68 *tons.* The arches are 120 feet span, and weigh about 2,500 tons each.

Vauxhall bridge was built between 1811 and 1816. The foundations of the piers of this bridge were built in caissons. An excavation was made down through the gravel stratum to the clay. It is a light structure, and no settlement is recorded.

New London bridge, built between 1825 and 1831. The foundations of the piers of this bridge are built in coffer-dams or caissons, the floors of which rest on piles under the entire area of the bases of the piers. The piles are about 20 feet long and 3 feet apart, penetrating the clay 18 to 19 feet. *On the heads of the piles* were laid sleepers; the loose earth between the heads of the piles is replaced with rubble concrete, on which blocks of stone and brick work filled up the spaces between the pile heads and immediately over the platform of oak planking which carried the first course of granite.

The pressure upon *each pile is* 80 *tons,* or 5 tons per square foot of the entire area of the pier. Each pier of this bridge settled from six to ten inches towards the down stream. No further settling is apprehended.

Hungerford bridge, built in 1844. This is a chain suspension bridge. On the Hungerford market side the ground under the mooring piers was very bad. Piles were here driven to the depth of 30 feet.

Chelsea bridge, built between 1850 and 1857. This is a suspension bridge. The foundations of the piers are on *bearing piles* of 14 inches square, 3′ 6″ apart, and driven 32 feet below low water, and about 16 feet into the London clay. (For other details of these foundations see Engineer Architectural Journal, for November, 1864.)

New Westminster bridge, built in 1858 and since. The arches of this bridge are of wrought and cast-iron. Elm piles, 32 feet long, are driven in alternate rows of 3 and 5 each, to the number of 145 *in each pier,* and 18 to 20 feet into the London clay, *each* tested to a bearing weight of 60 tons. Circumscribing the area into which the elm piles are driven, hollow cast-iron piles, 15 inches diameter, 25 feet long, are driven 4 feet apart, and between these, in grooves cast on hollow piles, flat iron piles are driven to nearly the same depth, forming a coffer-dam, within which all the soil overlaying the gravel bed is excavated, and concrete filled in to the top of the piles, which are cut off 6 inches below low water.

On the *heads* of the *elm piles* is a *course of stone covering two or three piles alternately,* upon this the bottom course of granite of large size is laid. The bearing piles are 14 inches square, driven at intervals of 1′ 9″ from centre to centre, to an average depth of 20 feet in the London clay. It will thus be noticed that the *solid stone piers* sustaining the iron arches *rest* upon the *heads of the wooden piles,* which stand a considerable height above the bed of the river; that these piles are within an enclosure of cast-iron and granite slabs; and around the piles and filling up the sides of the casing or enclosure there is a solid bed of concrete as good as rock.

At the Hull docks the load per pile per square foot is 37 tons; at the London bridge the load per pile per square foot is 80 tons; at the Albert warehouse, Liverpool, the load per pile per square foot is 80 tons; and at the New Westminster bridge it is 12 tons per square foot. And the pressure on the whole area of the foundation is only 2 tons, while on the old bridge it was 6 tons, and in the London bridge it is $5\frac{1}{2}$ tons.

REMARKS OF ENGLISH ENGINEERS ON THE LONDON BRIDGES.

The bed of the Thames is much lower than when the bridges which have failed were built, occasioned by the increased scour produced by removing the old London bridge. Whenever the foundations have been made to depend on the gravel, and have not been taken *deep into the London clay,* failure has taken place. In the clay only can a foundation be found.

The old *successful examples* are all of *one class*—coffer-dam examples, (excepting Vauxhall and Mr. Page's recent structures.) Vauxhall was a coffer-dam carried to the clay without piling; the weight of the bridge not needing piles.

All the other *sound bridges* are *piled deep into the blue clay.* The shoulders and sides of these piles, and the surface of the clay between them at their tops, are the ultimate bearing points, upon which presses the superstructure, whether of granite or other stone courses, or composed of concrete and wood or of iron.

The *concrete and iron casing* about the piers of the Westminster is believed to be a ten times stronger medium, for the retention of the *piles in their places,* than the London clay (at whatever depth) would be; and omitting, therefore, all aid from the external piles and casing in bearing the weight, we find that the 133 elm-bearing piles are alone capable of bearing a load four times greater than can be put upon them, and there is *not so much chance for unequal settling as with sleepers and bearing planks,* such as exist at the successful bridges. We *cannot find one instance* of *deep-piled bridges abroad which has fallen.*

In Venice the piles are *covered with a planking of flat-boards* under water. Whilst the London clay would only bear a pressure of 5 tons per foot, piles driven into it would carry 70 to 80 tons.

At the Hull docks the *piles* were 10 inches in diameter and carried a weight of 37 tons per foot superficial; at the London bridge the *piles* were 10 inches in diameter and carried a weight of 80 tons per foot; at the Albert docks, Liverpool, the *piles* sustained a weight of 80 tons per foot; at the New Westminster bridge the piles were 14 inches in diameter, and would have to carry only 12 tons per foot. It was stated that the elm piles used in the foundations of Westminster bridge would carry 200 tons without permanent deflection. (See Engineer and Architectural Journal, for 1858.)

The *compressibility* of oolitic and tertiary clays *can only be overcome by piling,* deep sinking, heavy ramming, or heavy weighting. The point of bearing must be carried below the possibility of upward reaction. The depth of a foundation in compressible ground ought not to be less than $\frac{1}{4}$ the intended height of the building above ground—that is, for a shaft of 200 feet the foundations should be made secure to a depth of 50 feet, by piling or by well sinking and concrete. (Engineer and Architectural Journal, for 1857.) Masses of concrete, brick or stone, placed on a compressible substratum, however cramped and bound, may prove unsafe. *Solidity from a considerable depth can alone be relied upon.* Mere enlargement of a base may not in itself be sufficient. (Engineer and Architectural Journal, for 1857.)

FOUNDATIONS OF THE GRIMSBY DOCKS ON THE HUMBER,

These docks were commenced in 1846. The entrance to them is beyond the low-water line, and advanced into the river $\frac{3}{4}$ of a mile. The ground over the whole area of the two entrance locks, centre pier, and wing walls was excavated 8 feet below the sill of the larger lock, and bearing piles were driven in rows 5 feet from centres, and in some places 4 feet over the whole area. A pile was considered sufficiently driven when it moved not more than $\frac{1}{4}$ of an inch with the blow of a ram of 1 ton falling 12 feet. *The heads of the piles were then cut off to a uniform level, the ground was removed to a depth of 2 feet below this level, and the space filled with concrete.* Timbers so connected as to form continuous ties across the locks and centre pier *were then laid* transversely in parallel rows *on the bearing piles.* Other similar timbers were laid at right angles to the transverse bearers, concrete being filled in to the upper surface of these longitudinal bearers, which were then covered with planking as a bed for the masonry. (Engineer and Architectural Journal, for 1864.)

The result of European experience gives the following as the bearing weights supported by the foundations of the piers of several of the most remarkable and heaviest structures, in pounds per square foot:

Dome of St. Peter's, Rome	35,254 lbs.
Dome of St. Paul's, London	41,713 lbs.
Dome of the Invalid, Paris	31,862 lbs.
Dome of the Pantheon, Paris	43,440 lbs.
Column of the Basilica of St. Paul	42,950 lbs.
Steeple of the Church of St. Mary	63,325 lbs.

For the relation between the total surface *covered* and the *part occupied by its walls*, or the supporting parts and the above, see Rondelet, Vol. 3, p. 232.

PRACTICE AND EXPERIENCE OF UNITED STATES ENGINEERS.

We now proceed to give the practice and experience of the Engineers of the United States in the construction of foundations in different localities and in compressible soils. The dry dock at the Brooklyn Navy Yard, New York, was commenced in 1841 and completed in 1851. It contains 13,837 cubic yards of masonry, resting upon 38,532 cubic feet of pile timber.

The soil was found to be chiefly vegetable decomposition to the depth of 10 feet, and below this almost impalpable quicksand containing a large proportion of mica. When confined, and not mixed with water, it is very firm and unyielding, presenting a strong resistance to penetration. When saturated with water it becomes a *semi-fluid*, and moved by the slightest

current of water passing over or through it. Small veins of coarse sand were also occasionally encountered, through which flowed springs of fresh water. Borings were made to the depth of 80 feet, and brought up sand and clay and fresh water. There is but a small proportion of clay in any part of the foundation. The borings extended 40 feet below the foundation of the dock.

The foundations for the superstructure of this dry dock were placed 37 feet below mean tide and 42 feet below the surface of the ground. Black mica overlaid the quicksand under the coffer-dam. Under and in this coffer-dam 3,504 piles were driven, averaging 39 feet in length by 15 inches square.

The earth above low water was removed before the coffer-dam was formed, and about 10 feet in depth was removed by dredging. The *semi-fluid* state in which the material was found, after the water had been pumped out of the pit, was very difficult to remove. It was so fluid as to require tubs for its removal. Bottom springs of fresh water were found in about six feet of the required depth of the foundations. The largest discharged 10 gallons per minute. When flowing from a level of 26 feet below low water it discharged 38 gallons per minute, containing 27 ounces of sand; at a level of 22 feet it discharged 33 gallons per minute, containing 17 ounces of sand; at a level of 17 feet it discharged 10 gallons per minute, unmixed with sand.

These springs presented great difficulties in laying the foundations from the flowing of the water, which as it came up brought large quantities of sand, which, if continued to flow, would soon have endangered the surrounding works. The pressure of the water was so great as to raise the foundation however heavily it could be loaded.

The settling of the piles supporting the pump well was the first evidence of undermining from one of these springs. The site of the well was changed, but the spring followed and compelled another change of the well.

This spring was driven out of the old well by driving *piles* until it was filled up, but it immediately burst up among the *foundation piles* of the dock near by. In a single day it made a cavity in which a pole was run down 20 feet below the foundation timbers. 150 cubic feet of stone were thrown into this hole, which settled 10 feet during the night, and 50 cubic feet more were thrown in the following day, which drove the spring to another place, where it undermined and burst up through a bed of concrete 2 feet thick. This new cavity was repeatedly filled with concrete, leaving a tube for the water to flow through; but in a few days it burst up through a heavy body of concrete in a place 14 feet distant, where it soon undermined the concrete, and even the foundation *piles*, which settled from 1 to 8 inches, although 33 feet long and driven by a hammer of 2,200 lbs. falling 35 feet at the last blow, with an average of 76 blows to each pile, the last

blow not moving the pile ½ an inch. It was then determined to drive as many additional piles into the space by means of followers to force those already driven as deep as possible.

The old concrete was then removed to a depth of 20 inches below the top of the piles. An area of about 1,000 square feet around the spring was then planked, on which a floor of brick was laid in dry cement, and on that another layer of brick set in mortar. The space was next filled with concrete, and the foundations completed over all. Several vent holes were left through the floor and foundations. After a few days, when the cement had well set, the spring was forced up to a level of about 10 feet above the former outlet, at which it flowed clear without sand.

Two other of these springs were closed by freezing in 1848, and forced up in one case 800, and in the other 1,200 square feet of the foundations. This took place between the lower timbers and the planking, *lifting also the first course of the stone floor*, which was from 12 to 15 inches thick.

The whole number of bearing piles in the foundation is 6,549. They are chiefly round spruce timber 25 to 40 feet long, averaging 14 inches diameter at the head. The *average length* of all the *piles* driven was 32′ 7″. The piles were originally driven 3 *feet from centres*. Afterwards as many piles were driven as could be forced into the earth. Whenever a hammer of 2,000 lbs. weight, falling 35 feet, drove the pile for the last few blows exceeding 3 inches per blow, another and larger pile was driven along side.

With the exception of 541, all these piles were driven by hammers from 2,000 to 4,500 lbs. each, falling from 35 to 40 feet. The average number of blows per pile was 151 with the small hammers, and 50 blows only per pile with the large hammers. The 541 piles were driven with a Nasmyth steam-pile engine.

A trial round pile of (20″) twenty inches diameter at the butt, and (14″) fourteen inches at the small end, of 49 feet in length, was driven by a 2024-lb. hammer, falling finally 35 feet; forty-five feet below the foundations. The first 100 blows the hammer fell but a few inches; the next 260 blows drove the pile 30″ in 46 minutes; the next 260 blows drove ½″ to 1½″ per blow for 60 minutes; the next 110 blows averaged 1¼″ per blow for 60 minutes, the hammer falling the last blow 34 feet.

This trial pile subsequently received 200 blows through the medium of a follower which drove it an average of ½ an inch to each blow.

Another trial pile was driven 43 feet by a Nasmyth steam-pile driver, and then another pile 15 feet long, driven on top of the first, making a total penetration in the earth of 57 feet.

The first pile was driven 42 feet by 373 blows in 7 minutes, as follows:

4 blows, 4 inches each.
8 " $3\frac{1}{2}$ "
22 " 3 "
25 " 2 "
40 " $1\frac{1}{4}$ "
56 " $1\frac{1}{4}$ "
32 " $1\frac{1}{4}$ "
64 " $1\frac{1}{8}$ "
73 " 1 "
49 " $\frac{1}{2}$ "

The second pile was driven 15 feet by 2,400 blows in 43 minutes, as follows:

33 blows, $\frac{3}{8}$ of an inch each blow.
73 " $\frac{1}{4}$ " " "
100 " $\frac{1}{8}$ " " "
800 " drove it altogether 88 inches.
300 " " " 24 "
300 " " " 12 "
450 " " " 11 " and the last,
350 " " " $5\frac{1}{2}$ "

The movement of these piles indicated the continuance of the same material to the depth which they reached.

The foundation was mostly laid as follows: The excavation being completed to the proper depth, and piles cut off to a uniform level, 2 feet in thickness of *concrete* was *rammed between the bearing piles.* These piles were then capped with 12 and 14 inch yellow pine timber, laid transversely with the axis of the dock, and *treenailed* to each pile. The concrete was then raised to the top of these timbers, and a light flooring of three-inch yellow pine plank was laid upon and spiked thereon. Another course of similar timber was then placed upon this floor, breaking joints with those below, to which they were treenailed. The intervals were next filled with concrete, and another floor of 3-inch plank spiked down; which completed the foundation.

The amount of work done by the heavy Nasmyth hammers was at least $\frac{1}{3}$ greater than that done by those whose hammers were only $\frac{1}{2}$ the weight. This Nasmyth hammer, of 4,500 lbs., was worked with very short rapid blows, raised a height equal only to the stroke of the engine.

The support of this foundation is derived mainly from the adhesion of the material into which the piles were driven and slightly from their sectional area.

It was ascertained that it required a weight of 125 tons to draw up one of these piles, or rather to start or put it in motion, when driven 33 feet to the point of ultimate resistance, with a ram of one ton falling 30 feet at the last blow. The piles averaged 12″ in diameter in the middle, making at least a support of 100 tons per square foot of foundation.

PILE FOUNDATIONS AT THE PHILADELPHIA NAVY YARD.

At the site of the dock of the Philadelphia navy yard, commenced in 1849, the first stratum of soil is a mud of rich loam extending from a little above low-water level, declining toward the bottom of the river, which is of a clean gravel, to the depth of about 24 feet below ordinary low tide, and evidently the deposit through a long period of years of the earthy matter held in suspension by the waters of the Delaware river, upon a stratum of sand and gravel forming the bed of the river. The sand and gravel are not more than from 4 to 7 feet in thickness, before those substances become mingled with paving stones, large boulders, and to some extent with clay, forming a species of hard pan, to which all the piles used in the construction of the foundations of the work were driven. The object of the foundation of the basin of the dock was to give support to its bottom and to secure its outer edge against the action of the current of the river. As the excavation was completed, piles were driven 4 feet apart from centres in rows from one end of the space to the other. An extra row was driven under the line of the walls of the three sides of the basin. A space was then formed by drawing a line of sheet piling eight feet from the inner line of piles of the coffer-dam. Two extra rows of piles were driven within this space, which was then filled with concrete to within 2 feet of the floor of the basin. The piles thus driven were cut off to the same level, capped with timbers one foot square, and the spaces between these capping timbers filled with earth and concrete. (Stewart's Dry Docks of the U. S.)

PILE FOUNDATIONS AT THE PENSACOLA NAVY YARD.

The dock at the Pensacola navy yard was built in 1851 and 1852. The soil of this locality is clean white sand to a depth of about 40 feet, resting upon a bed of soft clay. The sand is so open and porous that a cubic foot of it, when saturated, contains 6 quarts of water.

A space of 140 feet wide by 380 feet long was inclosed by driving yellow pine piles, 12 inches square, to the depth of about 20 feet into the sand, placed in contact with each other, for forming a coffer-dam. Within this space, secured by other means against filtration, the sand was excavated to a depth of 14 feet below tide.

After a section of the pit had been excavated to the level of the foundations, the bearing piles were driven in rows 4 feet apart, and 4 feet from centres in each row, until a ram of 2,200 pounds, falling 30 feet, could not move them more than $\frac{1}{2}$ an inch. *Upon* the transverse rows of piles, cap

timbers, 12 inches square, were placed, and the space between the timbers filled with sand. The timbers were then covered with 5-inch plank, spiked to the caps, and the whole floor caulked with wedges. On this floor the masonry of the basin was commenced. This foundation was tested and found satisfactory. The experimental tests showed that a single foundation pile, as a *fulcrum*, sustained nearly 39 tons without settlement; and it required 41 tons strain to draw a pile that had been driven 16 feet into the sand.

The railroad bridge at Havre-de-Grace, on the Susquehanna river, was commenced in October, 1862, and finished in November, 1866.

The foundations of the piers of this bridge are referred to as examples of piles driven in the compressible bed of the river, supporting an iron caisson on a grillage of timber resting on the piles, and a caisson lowered to solid rock through 15 feet of compressible soil.

In 1863 piles were driven and sawed off 40 feet below the surface of the water for the foundation of pier No. 3; a platform or grillage of timber, strongly ironed, upon which the pier was to rest, was constructed near the site of the work and floated over the site of the foundation under which the piles had been driven. This platform was placed between two substantial construction piers of timber; lowering screws, 6 in number, of $3\frac{1}{2}$ inches diameter, were attached by hooks to the platform; and to the construction piers a section of an iron caisson was constructed, resting upon the wooden platform thus suspended. The masonry was then built within the caisson, lowered by means of the screws as it approached the top of the section, when a second section of the iron caisson was added, built within and lowered by the screws in like manner as the preceding, and thus continued until the grillage or wooden platform rested upon the heads of the piles.

Another pier (No. 7) was founded on the rocky bed of the river underlaying the compressible bed of the stream for a depth of 15 feet. This latter had been displaced in several places by the spring freshets of 1865, rendering piling impracticable; all the earth was, in consequence, removed down to the surface of the rock. At the site of this pier the rock bed was 18 feet below the original undisturbed bed of the river. To remove this earth a wrought-iron foundation caisson, averaging 8 feet in height and about 50′ by 20′ square, was lowered so as to enclose the site of the pier. This was gradually depressed to the rock by removing the earth within it by means mainly of powerful pumps, aided by the constant exertions of skilled divers. The masonry was then laid within the tank upon the solid rock, and being brought to a level some feet below the top of the foundation caisson; the caisson of the pier resting upon the platform of timber was lowered and built upon. The foundation of this pier was 36 feet below low water. (See Engineer and Architectural Journal, April, 1867.)

RESISTANCE OF PILES TO PRESSURE.—FORT RICHMOND, STATEN ISLAND, NEW YORK.

The soil of part of the foundations of Fort Richmond, now Fort Wadsworth, on being excavated to low-water level, was found to be very compressible, with springs discharging large quantities of water. The scarps and counterscarp of the southern half of the land front and face of the adjacent bastion of the water front were situated on such a soil, resembling that of the dry dock at Brooklyn. The weight to be sustained was a granite casemated battery of four tiers of 8 and 10 inch guns, with the shot, shell, and other munitions therefor. The scarps, piers, and arches, are all of granite.

Piles were in this case resorted to, and no settlement has since been noticed. The work was commenced in 1856, and finished to receive its armament in 1861. The piles were 30 feet long, 12 inches square at the head, and not less than 10″ at the small end. They were driven by a hammer of 1,800 pounds weight, with blows in quick succession, the last blow of the hammer being from a height of 45 feet. They were cut off level with the surface of the ground, and capped with large flat stone, covering the heads of from 3 to 5 piles—the joints being filled with concrete, well rammed. A second layer of large flat stone, breaking joint with the first, on which the masonry of the granite scarp was commenced. It will be noticed that there was no timber grillage covering the heads of these piles.

RESISTANCE OF PILES TO PRESSURE.—EXPERIMENTAL TESTS AT PENSACOLA.

In 1851 a series of experiments were made, under the direction of a special board of officers, on the resistance, etc., of the piles driven for the foundations of the dock of the navy yard at Pensacola. A pile that had been driven six days, surrounded by other piles 4 feet distant from centres, of 30 feet in length, averaging 13 inches diameter about the middle of its length, round, with bark on, was first selected for these experiments. The average depth of the pile in compact sand was 15 feet, driven by a hammer of 4,087 pounds, and 69 blows at the rate of $2\frac{1}{2}$ blows per minute.

The first experiment, made on the 17th of May, was the application of a power (by pressure or loading) of 23,850 pounds to a pile for 5 minutes, which it bore without moving. The second experiment was by applying a power of 20,000 pounds to another pile; a third pile was subjected to the same strain for 5 minutes, and a *fourth* pile resisted the same power for 5 minutes. There was then applied to this last pile 31,360 pounds (14 tons) for several minutes. Three other piles were subsequently tried, and each resisted 22,400 pounds (10 tons) pressure for 5 minutes.

The next test was by pulling up the piles, beginning with 22,400 pounds, applied to the pile No. 4, before noted, increasing the power one ton every two minutes—that is, after 10 tons had been applied for 2 minutes; then 11 tons were applied for 2 minutes; then 12 tons, and so, until 15 tons, or 33,600 pounds, pressure had been tried, when a hook of the steelyards broke. Three days afterwards the experiment was resumed, beginning with 10 tons, gradually adding ton by ton, until there was $31\frac{1}{2}$ tons of upward strain acting upon the pile. This experiment lasted 1 hour and 40 minutes, during which time the power upon the pile was constant.

There was afterwards a gradual increase of power to 39 *tons* without moving the pile. It then resisted 40 *tons* for $\frac{1}{2}$ a minute, when it *began to rise* slowly. 41 *tons* were then applied for $1\frac{3}{4}$ minutes; then $41\frac{1}{2}$ tons for half a minute, the pile meanwhile moving upwards at the rate of $\frac{1}{12}$ *of an inch per minute.* The tests of 40, 41, and $41\frac{1}{2}$ tons occupied half an hour, during which, the strain being constant, the pile was moved $2\frac{1}{2}$ inches.

It was then subjected to a strain of 30 tons for 18 hours, and was not moved by it. After which, by adding from 2 to 7 tons, the pile was moved, in one hour, three (3) inches; and, after it had moved upwards about 6 inches, a power of 25 tons was allowed to remain on it for 2 *days* and did not move it. The pile was then withdrawn from the sand. Its extreme length was 29 feet. The length of the part which had been in sand was 16 feet, including the sharpened end of 2 feet in length; 1 foot in depth about this pile was *loose sand*, which had been once excavated and fallen back. The average diameter of the part in the sand was $13\frac{1}{2}$ inches, including the bark. The bark remained on the entire pile, except on $3\frac{1}{2}$ feet of its pointed end. This pile weighed 1,632 pounds.

A single pile used as a fulcrum for the lever sustained at the most, during the experiment, $38\frac{96}{100}$ tons weight without settlement. Experiments showed that piles which one day penetrated $\frac{6}{10}$ of an inch per blow, of a 4,087 pounds hammer, falling 10 feet, was found to penetrate $\frac{1}{8}$, $\frac{1}{2}$, and $\frac{6}{10}$ of an inch by 3 similar and successive blows applied the following day—the three blows being given in 1 *minute.* If the pile is allowed to remain undisturbed a short time the power to move it afterwards is greatly increased. (Stewart's Dry Docks of the United States.)

McALPINE AND SANDERS' FORMULA FOR BEARING WEIGHT OF PILES.

The formula deduced by the engineer, Mr. McAlpine, from his labors at the Brooklyn navy yard, applicable to rams of 1,000 lbs. to 3,000 lbs., falling from 20 to 30 feet, was $\chi = 80\,(W + .0228\ \sqrt{F-1.})$ In which χ was the supporting power of a pile driven by the ram W, falling a distance F; χ and W being in tons, and F in feet—and that not more than $\frac{1}{3}$ of the result given by this experience should be borne or relied upon for any piles.

Major Sanders' formula, deduced from his experience in driving piles at Fort Delaware, with a ram of 3,500 lbs., falling $3\frac{1}{2}$ feet, driving a pile 4′.2; is $\frac{3500 \times 42}{8} \frac{R \quad h}{+ 4'.2} \frac{d}{} = \frac{35000}{8} = 4375$ lbs., the weight which the pile would bear with safety. (See Stewart's Dry Docks of the United States, and Engineer and Scientific Journal, for 1867.)

FOUNDATIONS OF FORT MONTGOMERY ON PILES AND GRILLAGE.

The foundations of Fort Montgomery, on Lake Champlain, near the latitude of 45°, was commenced in 1844, and the driving of 4,383 piles was finished in 1846. These piles were capped with a timber grillage in 1848. *Each pile* was calculated to sustain a weight of 7 cubic yards of masonry and $1\frac{3}{4}$ yards of earth, or a total weight of 34,125 lbs., or 15.27 tons.

The piles were driven about 3 feet apart. The grillage is in two courses, the lower one, 1′ 3″ wide and 12″ thick, is notched down 4″ on the heads of the piles, and pinned thereto. The upper course at right angles to the lower one is 12″ square across the piles, and 12″ × 8″ between them, the 12″ × 12″ being notched 4″ down on the lower course, thus giving a level floor for the masonry. The length of the piles, after being driven and cut off, was from 29 to 33 feet. The fall of the hammer at the last blow was from 35′ 8″ to 36′. The diameter of the piles was from 12 to 16 inches at the butt and $9\frac{1}{4}$ to 14 inches at the smaller end. The last penetrations were from $2\frac{1}{2}$ to $6\frac{1}{2}$ inches. These facts apply to 39 piles given as examples and illustrations of the whole. The hammer weighed 1,630 lbs. The weight of the spruce piles was about $39\frac{3}{5}$ lbs. to the cubic foot. The pile weighed was rather more dry than the average. At least 40 lbs. to the cubic foot would be a proper average.

The compressibility of the soil into which these piles were driven was about one-ninth $(\frac{1}{9})$ of its entire bulk.

COLONEL MASON'S FORMULA FOR BEARING WEIGHT OF PILES.

Colonel Mason deduces the following formula from an investigation of the value of this foundation, or the amount of weight with which each pile may be loaded: Let h be the height of the fall of the hammer at the last blow, s the distance to which the pile penetrates at the last blow, 1,630 lbs. the weight of the hammer, 960 lbs. the weight of a pile 24 cubic feet, and joint weight of pile and hammer 2,590 lbs.; g the force of gravity $(32'\frac{1}{6},)$ or the velocity that gravity will generate in a second of time, and $\sqrt{2\,g\,h} =$ velocity of hammer as it strikes the pile, $\frac{h}{s}$ is $\frac{36'}{3''.75} = 115.2$, and we have for the value of the retarding force $1{,}630 \times \frac{1630}{2590} \times 115.2 = 118{,}175$ lbs., or 52.75 tons. Each pile was actually loaded with and supported the average weight of 28,575 lbs., or 12.75 tons, besides its own weight (960 lbs.) and that of the grillage, or about $\frac{1}{4}$ of that which the calculated force of resistance is capable of holding in equilibrio.

In the above case the *velocity* of the hammer at the moment of impact will be $\sqrt{2 \times \underset{h}{36} \times \underset{g}{32\frac{1}{6}}} = 48.125$ feet per second, and the velocity of the joint *mass* of hammer and pile will be $48.125 \times \frac{1}{2}\frac{6}{5}\frac{3}{9}\frac{0}{0} = 30.3$ feet per second $= V'$, and the retarding force $\frac{V'^2}{2s}$ will be $\frac{30'.3}{7''.5} = \frac{918'}{7''.5} = 1{,}468$, the velocity that the retarding force is capable of destroying in a second of time on the joint mass of the pile and hammer is then 1,468 feet. But gravity is capable of generating on that mass a velocity of $32\frac{1}{6}$ feet; dividing 1,468 by $32\frac{1}{6}$ we have 45.63 as the ratio between the *retarding force* and the *force of gravity*. That is, the *retarding force* is capable of holding in equilibrio 45.63 *times* the joint weight of the *pile and hammer*, or 2,590 pounds $\times$ 45.63 $=$ 118,181 pounds. This is within six (6) pounds of the previous result. The time (t) in this case will be $t = \frac{2s}{V'} = \frac{7''.5}{30'.3} = \frac{2}{97}$ of a second.

The same result may be obtained by dividing the velocity destroyed, viz, 30′.3, by the velocity the force is capable of destroying in a second of time, viz, 1,468; or $\frac{30.3}{1468} = \frac{2}{97}$ on the supposition of a constant force during the short period that it takes to destroy the motion of the pile, instead of a retarding force. Colonel Mason concludes his memoir with the deduction that Fort Montgomery experience is in favor of a coefficient of stability of $3\frac{6}{10}$ when applied to the calculation under the supposition of a constant force, although it in reality, as a general rule, decreases by very small decrements towards the terminal penetration; and hence, taking this coefficient as a constant, is erring on the safe side. For a more minute detail of Colonel Mason's investigation of this subject see papers on Practical Engineering No. 5, by Colonel J. L. Mason, Corps of Engineers, U. S. Army, 1850.

Major Sanders' experiments at Fort Delaware were made with a view of deducing a rule for foundation on compressible soils, without any firm substratum lying within reach of piles, for calculating what weight each pile would bear with safety, by comparing the distance it was sunk at the last blow with the force of the blow, it being understood that the pile has been driven to such an extent that for a number of blows the penetration has been uniform for equal blows. To ascertain such a rule two sets of piles of four each were driven, and a platform built on their heads; they were then loaded with blocks of stone piled regularly on the platform; and at regular intervals of time the amount of subsidence caused by the weight, which was periodically augmented, was noticed. These piles were *not driven* through the alluvial; their points were about 20 feet from the sandy subsoil, so that their stability was due to the accumulated and constantly increasing resistance of the same medium.

In one experiment the four piles were driven to a depth of about 24 feet each, with a pile-driver that struck 34 blows in a minute, with a ram of 2,000 pounds, and a uniform fall of 6 feet. An artesian well sunk on this island in 1834 found mud continuously to a depth of 46 feet below low-water mark, then 20 feet of sand, then 30 feet of coarse sand containing shells. It then entered and penetrated for 47 feet a bed of marl, which contained bowlders. At the penetration of 24 feet, each of the blows of the ram drove them about an inch, or exactly $\frac{1}{74}$ of the fall of the ram. The weight placed on them at first was about 60,700 pounds, (or about $\frac{1}{9}$ of the product of the friction and the weight of the ram.) This weight caused a subsidence in 6 months of $\frac{6}{32}$ of an inch, when 15,000 pounds were added without increasing the subsidence. Upon again increasing the weight till it reached 94,000 pounds, (the ratio corresponding to which was $\frac{1}{6}$,) the subsidence began again, and in a month had attained $\frac{8}{32}$ of an inch, when it ceased, or at least made no progress during the ensuing three months. The next addition to the weight brought it to 107,500 pounds, and the ratio to about $\frac{1}{5}$, and in a month increased the subsidence to $\frac{9}{32}$ of an inch. The next addition raised the weight to 121,800 pounds, and the ratio to 1:4.6. This weight remained upon the piles *without alteration* until three years and five months had elapsed. In the first eight months it had caused the subsidence to increase from $\frac{9}{32}$ to $\frac{16}{32}$ of an inch; and this subsidence did not increase during the remaining two years and nine months of the period. During the ensuing seven months the weight was successively increased to 134,000, 147,000, 160,000, 174,000, and finally to 189,500 pounds, (or 84.59 tons;) the ratios corresponding to which were respectively 1:4.19, 1:3.81, 1:3.52, 1:3.23, and 1:2.969. Until the last weight was put on no additional subsidence was caused by the increased pressure. It will be seen that the weight, answering to the ratio of 1:4.6 above mentioned, remained upheld 3 years and 4 months without the slightest variation in the subsidence of the piles, although it was repeatedly added to, and the whole system jarred in doing so during that period. But upon laying of the last load of stone the subsidence again began, and at the end of the ensuing period of 1 year and 5 months had arrived at $\frac{26}{32}$ of an inch.. This subsidence did not go on uniformly, but by steps at a time. It seemed to be ceasing at the end of the period, judging from the facts that the intervals of rest were longer and the successive subsidence less towards that date, viz: April 12, 1856. The next time that the observations were made on the levels of the pile heads was on the 24th of April, 1860. The subsidence had then arrived at an average of 1 *inch* within an appreciable fraction, showing an increase in 5 years and 5 months of $\frac{6}{32}$ of an inch. It is probable that this subsidence took place within the 2 or 3 years that followed the date of April 12, 1856, and that the piles have remained immovable for the last 2 years at least.

The whole period over which this experiment extended was (May, 1860) about 9½ years. The conclusions that may be derived from it are obvious; that the subsidence had ceased may be safely assumed. It follows that a building on piles, driven in soils exactly of the nature of that in which these experimental piles were placed, will be safe if we do not load them with a greater weight than the *third part of the quotient arising from dividing the product of the weight of the ram and the distance it falls by the distance the pile is sunk by the last blow.* The coefficient was, however, fixed by Major Sanders for safety at ⅛. Conversely, having given the weight of the superstructure, we can by the same rule ascertain the minimum number of piles that will sustain it if driven to a fixed depth, or the depth to which an approximately fixed number of piles must be driven to effect the same purpose.

There were two experiments of the kind we have described made at Fort Delaware. The second one continued 3½ years, had similar results, and was equally regarded in the determination of the coefficient used in the rule.

From other experiments made during the same period, Major Sanders ascertained the relation between the living force of the ram and the distance the pile is sunk for *different falls* by a series of experiments on 64 piles, which received 1,900 blows from a ram of 800 pounds. It was found that when the fall was less than 3 feet, the useful effect was extremely small; that it gained in a rapidly increasing ratio as the fall was augmented, a foot at the time, to 5 feet; and at this point the ratio of useful effect to the force expended is at its maximum, and that the piles are driven to distances proportional to the blow; or, in other words, that there is nothing gained by increasing the fall beyond 5 feet—for example, 2 blows of 5 feet will sink a pile as much as 1 blow of 10 feet; 3 blows as much as 1 of 15 feet; 4 blows of 5 feet as much as 1 of 20 feet. It was also found that if the 5-foot blows followed each other in rapid succession the useful effect was rather greater than if the interval employed in common hand-power machines for hoisting the ram was allowed to elapse.

From 1833 to 1838 eleven thousand (11,000) piles, of 45 feet in length, 12 inches square at the head and not less than 10 inches diameter at the small end, were driven for the foundations of Fort Delaware, under the superintendence of Captain Delafield, of the Corps of Engineers, with a hammer of 1,800 pounds, by blows in quick succession, with steam power—the maximum fall of the hammer being 45 feet. Since 1850, four thousand five hundred (4,500) additional piles were driven under Major Sanders' superintendence, from which experience he has drawn the preceding deductions. Six thousand six hundred of these piles are under the scarps and casemates of the present work. (See Lieut. Morton's Life and Services of Major John Sanders, of the Corps of Engineers, 1861.)

In 1848 the excavations for the foundations of the work existing at this time (1868) were commenced and completed in 1849, and the piling by Major Sanders, heretofore referred to, was finished in 1851. By 1853 two thousand tons of masonry had been laid on these piled foundations, and in 1859 the walls, arches, and other masonry were finished.

Three bench marks were established in 1854, reference to which was made in 1859, when it was found the masonry had not settled in any part.

From 1859 to October, 1866, the settlement on reference to the above bench marks was 4″ at the maximum point, and 2″.65 at the minimum, and a mean settlement for all the observed points of 3″.19. No crack was perceptible in any part of the work in 1866 or in 1868. (See Reports of Superintendent at Fort Delaware.)

RESISTANCE OF PILES DRIVEN AT THE S. W. PASS OF THE MISSISSIPPI RIVER, ON STAKE ISLAND.

Stake Island consists of two mud lumps, forming its northwest and southeast extremities, about 500 yards apart. At both points the ground is high, of the character of other mud lumps.

The space between the two mud lumps is much lower, presenting the same general features and vegetation as the land on either side of the river. The ground between these two lumps is about as solid as anywhere higher up on the river between the passes and the city. The experimental pile driving commenced on the 19th November, 1867.

Pile No. 1 was 30 feet long. After 12 blows the *head* of the pile, within 1′ 6″ of the ground, was rent to pieces. The head of the pile was square timber, 11 inches at the upper end and 10 inches diameter at the lower end, banded with ½-inch iron 3½ inches wide. Outside diameter 9½ inches. The broken part of the pile was then cut off, and a piece 15 feet long set on top of it. 17 more blows were then given, when the pile gave way, tearing the head completely off. The total depth obtained by these 29 blows was 41′ 11″, being driven to low-water mark, and level with the lowest soil.

Pile No. 2, after 12 blows, was broken at the head, cut off, and a piece of 17 feet in length set upon it. 23 additional blows drove the pile down to 45′ 1″ below the surface of the ground.

Pile No. 3, 30 feet long. After 11 blows the head of the pile was badly rent 4′ 6″ above ground. 3′ 9″ were cut off, and a piece of 18′ 6″ set on, when with 9 blows the head gave way. 5′ 1″ was then cut off, and with 7 more blows the pile was 35′ 8″ below the surface.

Pile No. 4 was the same size as the previous piles. After 10 blows the head was 1′ 8″ above ground, and was then cut off and 16 feet set on; 27 more blows were given, and 1′ 9″ cut off; when a piece of 16 feet was set on, and after 13 more blows 4 feet were cut off, leaving the pile 54′ 2″ in the ground and 5 inches above.

The maximum fall of the hammer was 28 feet. The size of the hammer, of cast iron, was about 2′ 5″ high, 1′ 8″ wide, and 1′ 1″ thick.

The penetration of these piles was as follows:

No. 1, with the first blow falling 5′ 9″, was 6′ 3″.
" 2, " " " 1′ 6″, " 7′ 8″.
" 3, " " " 4′ 3″, " 9′ 1″.
" 4, " " " 3′ 6″, " 11′ 4″.

No. 1, with the *last blow* falling 28′ 5″, was 10 inches.
" 2, " " " 28′ 7″, " 11 inches.
" 3, " " " 26′ 6″, " 9 inches.
" 4, " " " 25′ 5″, " 14 inches.

See Bonzano to Gen. McAlester, 9th January, 1868.

In March, April, and May, 1868, 45 piles, of 50 to 60 feet in length, were driven under the direction of General McAlester, at St. Joseph's Island, in the same alluvial soil as deposited from the Mississippi river.

The same remarkable uniformity of penetration, by the successive blows, was developed as at Stake Island. See McAlester's report of 5th May, 1868.

GRILLAGE FOUNDATIONS.

A third system of foundations for compressible soils is that of the *grillage*, resting on the natural formation on the surface or at any selected depth.

The following are examples of this character by engineers who have constructed many edifices on this principle in the United States:

The earliest structure of this character, of which the writer has information, is a building at the Balize Bayou of the Mississippi river, near the site of the pilot houses. It is of brick masonry, constructed by the Spaniards or French during the early settlement of the country, and apparently for a magazine. It had settled so deep, up to the year 1829, as to make it impracticable, at that time, to ascertain the uses to which it may have been applied. From the practice of the inhabitants of the country it is inferred, in the absence of positive knowledge, that a grillage was used in this case.

In 1807 a survey of the coast of the Mississippi had been made and the outlets of the Mississippi particularly examined to select the most eligible site, best material, and plan for a light-house. A commission, appointed by the President of the United States, in 1816, again explored the various mouths of the river and the different islands situated there, and concluded that the most proper situation was at the mouth of the *Northeast Pass of the Mississippi river*, on Frank's Island. They say "this site appears to have undergone all the changes experienced by the different islands here in the course of their formation and consolidation, being elevated about 3 feet

above the surface of the river, and the only island not covered with water during the last hurricane." They bored the island and found the soil, for 35 feet, a mixture of clay and fine sand, and to the depth of 50 feet, a dark-blue clay without any mixture of sand or vegetable matter. This clay grew harder as the borings descended. This commission designed a plan for this locality, the structure to be built of stone and brick, recommending that for a foundation, the surface to be covered by a light-house, be dug down to the level of low water, and this *space be filled with piles* 25 *feet long*, one foot diameter, driven as close as possible, and as long as they can be forced down with the "*battering ram*," then cut off at the surface of the water, laying upon their heads one foot square timber of the greatest length that could possibly be procured, and not more than 1′ 6″ apart, crossing these with another layer of the same dimensions, filling the intervals between the timbers with shells, or rubbish beaten down and united by pouring in grout; covering this with a close floor of 4-inch plank, spiked to the timbers. Upon the floor the foundations may be laid, taking the precaution to turn reversed arches under all the walls. The *weight to be diminished comparatively* by making it *bear on the greatest surface possible*. (See State Papers on Commerce and Agriculture.)

A light-house of stone and brick masonry was afterwards built at this locality. After being finished it soon settled irregularly, and finally inclined to one side so much as to make it necessary to take down the whole structure before the year 1824. Soon after which period the material was in part transported to and used in the construction of Fort Jackson, about thirty miles up the river. By reference to the original drawings of Mr. Latrobe, (who constructed the building,) and loaned me by his brother, Benj. H. Latrobe, of Baltimore, it appears that the masonry of this tower was 81½ feet high, and 19 feet diameter at the base, resting on 53 piles of ten feet in length.

The foundations of *Fort Pike*, on the Rigolets, were commenced about the year 1820. The soil is very similar to that at the mouths of the Mississippi, the surface being mostly vegetable matter underlaid by a combination of vegetable earths and dark clay. The foundations of the scarps and piers of the casemates were all laid on a grillage of round pine logs, side by side, resting on the excavated soil, and crossed on top, at right angles, by similar logs of from 10 to 12 inches diameter, and about two feet apart in the clear. The masonry of the piers was built in and thus united to the masonry of the scarps. The work was finished about the year 1828. The foundations are about six feet below the level of the waters of Lake Pontchartrain, and the ground below that level is saturated with water.

The work settled irregularly. The masonry of the casemate piers broke from the scarps, making cracks about 4 inches wide. The timber grillage

in this case failed to overcome the compressibility of the subsoil or to preserve uniformity of settlement. (Personal recollection.)

Fort Wood, on the Chef Menteur Pass, (La.,) (now, 1868, Fort Macomb,) was commenced about the year 1825 and finished in 1832. It is situated at the end of a dry clay ridge following the bank of the Métairie Bayou, from near New Orleans, to the entrance of this bayou into Pass Chef Menteur, and is the firmest soil on which any of the forts in Louisiana are constructed, the natural surface being 3 feet above the waters of the Pass and Lakes Pontchartrain and Borgne. This dry ridge is wooded with heavy live-oak timber. The foundations of the scarps and casemates are similar to those of the fort on the Rigolets, and the general plan of the work similar. It was finished about the year 1832. The foundations were about six feet below water, and the ground saturated from the lake level to the depth of the excavations. The excavations were in a firm adhesive clay soil; hand pumps and buckets sufficed to keep down the water during the excavations.

In this case there was no such irregularity of subsidence as to injure the work, although extensive repairs were necessary in consequence of this irregularity. The grillage did not suffice to overcome the compressibility of the subsoil or preserve uniformity in the levels of the masonry. (Personal recollection.)

The foundations of *Fort Jackson*, Placquemine bend of the Mississippi river, were commenced in 1825; the masonry was finished and ramparts formed, ready to receive the parapets, in 1832, at which time the work was suspended to give time for settlement. The subsoil in this case is very compressible, and saturated with water at all times from near the surface to and below the bottom of the foundations, about 11 feet below the natural level of the country. Vegetable matter composed the upper layers, under which it is combined with dark clay. The problem in this case was to create uniformity of pressure and settlement by underlaying the masonry with a strong grillage of timber laid on a plank floor. The plank was laid on the excavated earth, and large cypress timber, 12 inches thick, 15 to 24 inches wide, laid longitudinally upon it, edge and edge, formed a solid continuous floor. On the top of this solid flooring other timbers, 12 inches thick, and from 15 to 18 inches wide, were laid 3 feet from centres, perpendicular to the lower courses. The spaces between these last timbers were filled, solid, with brick masonry laid in cement mortar. This grillage projected three feet in front and rear of the fair masonry of the scarps, which were from 8 to 10 feet thick. The grillage and foundations of the casemates were constructed in like manner. The result, seven years after the commencement of the foundations, was unequal settlement of various parts of the work, and cracks in the masonry of the scarps on the faces and flanks of the bastions. It became necessary to lighten the load of embankment pressing on the foundations. The earth pressing against the centre of the

scarps of the bastion faces and of the solid curtains was removed to the depth of the grillage of the casemates, and hollow vertical brick cylinders, of 18 feet diameter, covered with hemispheres of brick masonry, were constructed behind the faces of the bastions, and three horizontal bomb-proof storerooms were built on the centres of the solid curtains.

No stronger or more substantial grillage is known to have been constructed in Louisiana. In 1842 the casemates of the two water fronts and gate-way fronts were a second time loaded with an excess of weight to restore the levels and guard against future inequality of settlement. In 1851 the floors of the casemates of the flanks had to be raised and other repairs made, in consequence of unequal settlement.

The grillage failed to preserve uniformity of settlement, and the compression of the subsoil was not overcome by this application of a timber platform distributing the weight over a great surface. (Personal knowledge.)

Battery Bienvenue, on the bayou of this name, emptying into Lake Borgne, was commenced about the year 1828. It is founded upon a grillage of round pine logs, averaging 12 inches diameter, laid on a plank floor, and overlaid by 12-inch pine logs at right angles to the lower layer, and distant about 3 feet from centres. This grillage is founded four feet below the surface of the water of the bayou. The soil is but little better than a prairie tremblante. Borings were made 20 feet deep, indicating vegetable soil only, combined with a large percentage of water. The grillage is arranged precisely similar to those of Chef Menteur and the Rigolets. The masonry consists of a low scarp, backed by an earthen rampart. The masonry settled several feet before the scarp was finished, with great irregularities; the centre of each line of the trace of the work settling some feet below the ends. A square magazine, built on an independent grillage, similar to that under the scarps, settled, soon after the bomb-proof arch was turned, several feet, bringing the lintel of the door-way down to the surface of the ground. In this case the grillage failed to either secure a uniformity of settlement or overcome the compressibility even to such an extent as to fulfill the desired useful purpose. Great and extensive repairs and additions have been since made to this work. (Personal recollection.)

Southwest Pass Light-house was built in 1831. It is about 65 feet high, and built of wood. It rests on a timber grillage of unknown dimensions. It has failed to secure the conditions necessary for a foundation and has now to be rebuilt, having inclined so far from the vertical as to render a hastened reconstruction desirable. The site of this light-house is on one of the upheaved islands common to the mouth of this river. (Records of the Light-house Board.)

The *St. Charles Hotel*, in the city of New Orleans, was commenced in 1836 and finished in 1837. It was destroyed by fire in 1851. The foundations were of brick masonry, on a grillage of heavy flat-boat gun-

walls of 60 to 80 feet in length, 20 to 30 inches wide, and 6 to 12 inches thick, and laid about 6 feet below the sidewalk. This building settled 2 feet in 12 or 14 years. The present hotel (1868) was commenced in 1851, on top of the old foundations, and finished in 1853. It has settled fully 12 inches more (in addition to the settlement of the former building) in the last 15 years, making a total compressibility of the subsoil of 3 feet since 1837, or in 31 years. In this case a grillage has failed to secure the desired object. (Henry Howard to General Delafield, June, 1868.)

The *Light-house* at *Pass à l'Outre* was built in 1855. It is a cast-iron shell, about 65 feet high, resting upon a masonry base 4′ 6″ thick, extending a like distance (4′ 6″) beyond the base of the tower and under the whole structure. In 1864 an interior brick lining was added. It is not known that any timber underlays the masonry. This masonry, however, covering the entire surface occupied by the building, with 4′ 6″ offsets beyond it, fulfills all the conditions of underlaying timbers. The site on which it is built is firm on the surface and is about 3 feet above the level of the Gulf of Mexico. It must, therefore, be upon one of the upheaved islands common at the outlets of the Mississippi. It has settled unequally, one side leaning from 9 to 12 inches in its height.

In this case the grillage or masonry base has failed to secure either uniformity of settlement or to overcome the compressibility. The keeper's house at this locality is a 1½-story wooden structure, resting on 9 brick piers of 18 inches square each, under which is a grillage 6 feet square, of two thicknesses of round logs. It has settled 2½ feet and now requires repairs (1868) to correct the consequent defects. The grillage has in this case failed to secure the desired stability. (Bonzano's report to the Light-house Board, Washington.)

The *First Presbyterian Church*, in New Orleans, was commenced in 1846 and finished in 1857. The main tower is 20 feet square and 115 feet high, surmounted with a wooden spire. The foundations were built of brick masonry, laid in cement mortar, on a grillage of two thicknesses of flat-boat gunwales of forty-five feet in length, crossing one another. The excavation was 12 feet below the surface of the street. The bottom was a hard, stiff, blue clay, the best my informant has ever seen, after thirty years' practice as an architect in New Orleans. It has settled 5½ inches in 11 years. (Henry Howard to Gen. Delafield, June 1868.)

Fort Calhoun, now *Fort Wool*, Hampton Roads, Va., was commenced in April, 1819, when the first stone was deposited on the Rip-rap shoal for its foundation, in 21 feet water. The shoal and adjacent shores of the Chesapeake Bay and Hampton Roads are hard sand. It was determined to construct the superstructure of a four-tier casemated masonry battery at this locality, on an enrockment of quarry stone, thus forming an island similar to the Plymouth and Cherbourg breakwaters. During the first year's labor the enrockment was brought to the surface of the water on the

line of the southern face of the work, and in 1824 the surface had been enlarged to receive the entire foundations of the superstructure, for which preparations were made and commenced in 1826. The enrockment was added to, and an area of several acres was formed, terminating with a long slope, to intersect the shoal; equivalent to a grillage for the proposed superstructure, spreading the pressure of the walls at least 25 feet beyond their exterior lines. The foundations of the casemates on the water fronts were all laid, and the scarps and piers of the casemates raised to the springing lines of the arches of the embrasures, when numerous cracks in the masonry and irregular settlement of the work throughout its whole extent indicated that the foundations could not be relied upon. It was determined to suspend the construction of the work in 1829 or 1830, and load the foundations of the scarps and casemates with a weight greater than that of the castle in its finished state, with its armament, stores, and garrison.

In 1833, eleven thousand (11,000) tons of building stone were piled over and near the walls, bearing on their foundations.

In 1834, sixty-one thousand eight hundred and sixty-six tons (61,866) were added. The annual subsidence with this increased weight at the centre of the work was $\frac{1}{3}$ less than it was in 1833, and those parts that formerly settled most now settled least.

In 1835, twenty thousand tons more than the estimated required quantity was resting upon and along the whole extent of the foundations. This accession of weight continued to cause subsidence, though in a decreasing ratio.

In July, 1836, the stone for the superstructure and materials accumulated for compressing the foundations were being removed, upon the supposition that the base on which the castle was to rest had been satisfactorily compressed. In 1837 the load of stone was entirely removed from the foundations; continued subsidence was, however, observed, and the foundations were immediately reloaded.

In 1840, a total weight of 55,716 tons had been reloaded on the foundations, increased subsidence was still observed. In November, 1842, there was an excess of 13,627 tons on the foundations, beyond the ultimate weight to be supported. The average subsidence in 1841 was $\frac{7}{8}$ of an inch; compared with former years it was in a decreasing ratio. In 1843 it was found that the mass was still settling, when an additional load was recommended. In 1846 the subsidence was $\frac{3}{4}$ of an inch, and up to 1850 the diminution of settlement was progressive.

The total average subsidence of the foundations from 1830 to 1856, accurately noted from year to year, was at the greatest point 5.28 feet, and at the least 4.35 feet. It was immovable from 1850 to 1856. From 1841 to 1847 the maximum average settlement was $\frac{9}{100}$ of a foot. The total subsidence of a tide pier from 1824 to 1851 was 6.63 feet. (See Annual Reports of Chief Engineers, accompanying President's Message.)

Custom-house, New Orleans, (La.) This building was commenced in 1848, and progressed from time to time until 1860. It is founded upon a flooring of plank laid on the excavation seven feet below the street pavement. On this floor a timber grillage is laid of 12-inch logs, "side and side," over which similar logs are placed transversely, distant from each other 2 to 3 feet in the clear.

The space between the timbers is filled with concrete, which is continued over the whole grillage for a depth of one foot. Counter arches of $1\frac{1}{2}$ bricks thick support the walls of the interior subdivisions of the building, thus throwing the weight of the building upon the entire surface included within the outline of the building.

As a concrete and grillage foundation to support this heavy building, no greater surface, to resist the weight and pressure of the walls, could well be attained.

The walls of 2′ 6″ thick rest on grillage timbers 10 ft. wide.
Those of 4′ " " " 15 ft. "
And those of 9′ " " " 20 ft. " (abutments.)

In 1860 the granite walls of this building had been carried up 75 feet above the concrete base to the architrave line of the entablature, and all the iron floor beams of the fourth story finished.

The exterior walls are four feet thick, exclusive of projections; $2\frac{1}{2}$ feet of which is brick masonry, and $1\frac{1}{2}$ feet of stone masonry.

In 1851 a commission reported that borings at the custom-house, and at a point not far removed from it, indicated different degrees of compressibility. It is situated upon the firmest, dryest, and most reliable ground in and about the city of New Orleans.

The maximum settlement of the building in any one point, up to 1860, was 2′ 6″. This compressibility of the soil beneath the grillage was very variable.

From 1848 to 1851 the maximum settlement was 22.57 inches, and the minimum in the same time was 15.63, making a difference of level in various parts of the building of 6.94 inches.

In the year 1857–58, the maximum settlement was 3.50 inches, and the minimum 0.66, making a difference of settlement this year of 2.84 inches; and in 1858–59, the maximum was 2.63 inches, and in many places nothing, making a difference of settlement, level and compressibility, this year of 2.63 inches.

The line of the exterior walls in 1864, on which the temporary roof rests, varies in the level 3 inches.

This grillage covers a surface of about 300 feet square, and although well constructed, and with great care, it has failed in its objects. (See Records of the Treasury Department, Bureau of the Architect.)

Fort Sumter, Harbor of Charleston, was constructed upon an enrockment similar to Fort Calhoun, now Fort Wool. In 1840 the settlement was such as to induce the superintending engineer to recommend that it be loaded with a weight equal to the maximum, with its armament and munitions, that could rest upon its foundations. In 1850, the engineers reported the subsidence of this work to be continuous, though in a decreasing ratio annually. At this time the scarps and two tiers of casemate arches were completed.

CONCLUSION.

The plan proposed by a committee of the Light-house Board, in 1868, is again referred to the same committee, increased by two other members of the board to consider the whole subject anew. The plan then approved by the board is appended hereto; which, with the practice and views of many experienced engineers in compressible soils, is presented, with the belief that the best plan suited to this most difficult locality may be more satisfactorily devised with the information now embodied in this memoir for the consideration of the committee.

Extracts: "Considering the impracticability of finding any solid natural base at the outlets of the Mississippi, or any locality calculated to sustain the weight of an iron light-house, without extraordinary aids from art; and the extraordinary geological formation of the country about the Passes of the Mississippi, all going to show that great and unusual precautions are necessary to secure a foundation for any weighty structure at or about the outlets of the Mississippi, *the committee proposes some modifications of the plans submitted to it,* with the hope of securing greater solidity, and to a greater depth of the natural soil to resist the settling of an iron light-house for the proposed locality at the Southwest Pass."

"The first precaution is that the superstructure to rest on this foundation shall be of the least practicable weight to fulfill all the conditions for a permanent light-house, and then that the soil of the selected site be solidified to the greatest practicable depth by wedging it with wooden (pine) piles of about 50 feet in length, not less than 12 inches square at the head and not less than 10 inches diameter at the lower end, driven into the soil with a hammer of not less than 1,800 lbs. weight, with a final fall of 45 feet, continuing the operation of driving until the head of the pile may pass below the ways of the pile engine, and thence by a punch to the surface of the soil, or until the head of the pile, battered into fibres, no longer transmits the percussive action of the ram to the solid wood of the pile. These piles should be driven in rows, 3′ 6″ from centres, throughout the entire surface of the site to be occupied. After driving this series of piles a judgment can be formed of the practicability of giving additional solidity to the natural soil by driving another series of piles of the same

dimensions (or somewhat smaller diameter) at the intersection of the diagonal lines drawn from the heads of four consecutive piles of the first series, and 3′ 6″ from their own centres in their own parallel lines or roads."

"No more timber than of these two series can probably be driven into the soil. Should the contrary be the case, the site should be abandoned as approaching too near a semi-fluid to justify the construction of any permanent structure thereon."

"Having thus solidified the soil by wedging with timber, the heads of all the piles of the first series are to be cut off level, to a uniform depth of 2′ 6″ below the lowest low water, and the heads of the second series to a uniform level of 1′ 6″ below the lowest low water."

"The next operation will be to secure the heads of all those piles in a fixed position in relation to each other, and from being inclined by the superincumbent weight of the light-house. This will be effected by excavating the soil to a depth of 1′ 6″ below the heads of the first series of piles cut to a uniform level as above required; (it may be found more advantageous to make this excavation before driving any piles, to admit of floating the pile engine on a scow, a great economy where practicable;) or, to a depth of 4 feet below the lowest low water."

"The space below and between the heads of the first series of piles to the depth of 1′ 6″ will then be filled with concrete to the heads, care being taken to pump out all the water, that the concrete can be rammed thoroughly between the piles and into the soil on which it is first deposited. This concrete will be brought to the level of the heads of this series of piles, thus bracing them from each other by a hard, durable, and continuous mass of concrete of 1′ 6″ thick over the whole surface of the foundation."

"Over the heads of this first series of piles, and resting also upon the concrete surface between them, horizontal timbers (cypress or pine) will be laid, 12 inches thick by 15 to 18 inches wide, when another layer of concrete will be rammed about these string pieces and the heads of the second series of piles; then a row of horizontal 12-inch timbers at right angles with the first, of 15 to 18 inches wide, will be laid over the heads of the second series of piles, and concrete filled in solid to the surface of the second layer of horizontal bearing pieces. The string pieces resting on the heads of the piles may be treenailed thereto to keep them in place while the work is being constructed."

"We have now solidified the soil to a depth of 50 feet, and above it formed a solid floor of timber and concrete, resting upon and covering the entire base thus solidified by wedging."

"Upon this last surface, which is 6 inches below the lowest low water, completely excluded from the air, the foundation of the masonry for the support of the iron of the superstructure will be commenced."

The foundation of the base of the iron work should be four feet above ordinary high water. "This foundation, down to the level of the timber grillage, should be formed of solid brick or stone masonry, spreading out to cover the greatest possible surface, by offsets in every course of brick or stone of which this part may be constructed. Between this exterior base and the centre, the entire foundation will be raised with concrete to the natural level of the shoal. As these parts cannot have any weight of the superstructure (of the proposed design) upon them, any superfluous mass of material but adds to the risk of settling."

"The superstructure should be designed to throw the weight not only on the corner posts, but upon the spaces from one of these corners to the other, and also upon the radii connecting these corners with the centre column. With this in view the masonry on these lines, from the timber platform, should be built with offsets to cover as much surface as practicable. The bed-plate of the superstructure resting on the masonry should be bolted with composition bolts, securing them to the under part of the concrete and timber platform, to give some additional stability to the base against the action of the wind."

"Notwithstanding all these precautions, it is considered advisable, previously to raising the superstructure, to load the entire surface of this artificial foundation with a weight of matter greater than the entire load it can ever be required to sustain. This load should remain at least one year, when an examination should be made as to the propriety of commencing the superstructure, suspending the work, adding to the load and await another year, or abandon the site altogether."

The weight of cast and wrought-iron of the superstructure of the plan submitted to the committee is 400,000 lbs. This may be greatly reduced by the adoption of modification of the design of the framing of the wrought-iron work. Reference to the Practice of European Engineers for such structures may be found in Proceedings of the Institution of Mechanical Engineers for 1861, giving a detailed description of the light-house at Buda, Spain. Minutes of Proceedings of the Institution of Civil Engineers, vol. 23, for a description of the Ushruffee light-house in the Red Sea, and the Engineers' and Architects' Journal for Jan. 7, 1868, for description of the light-house for the Douvres.

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